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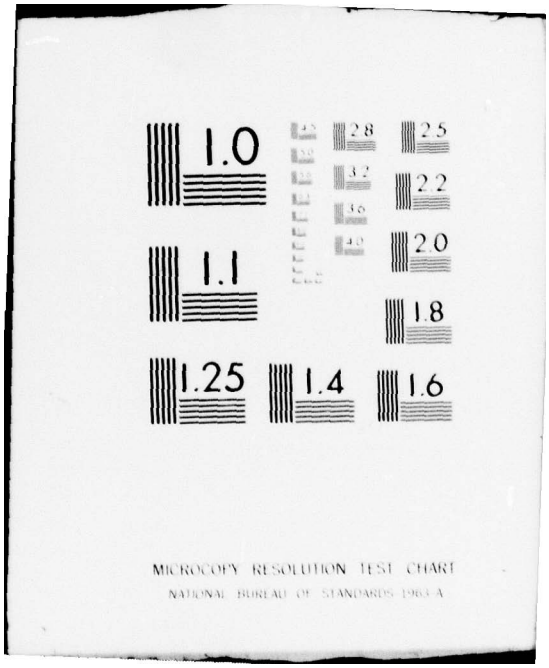
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Wave Runup on Rough Slopes

by
Philip N. Stoa

COASTAL ENGINEERING TECHNICAL AID NO. 79-1
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: CERC-CETA-79-1	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE *(and Subtitle)*: WAVE RUNUP ON ROUGH SLOPES.	5. TYPE OF REPORT & PERIOD COVERED: Coastal Engineering Technical Aid report
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s): Philip N. Stoa	8. CONTRACT OR GRANT NUMBER(s): 12 35p.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Department of the Army, Coastal Engineering Research Center (CEREN-CD), Kingman Building, Fort Belvoir, Virginia 22060	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: F31234
11. CONTROLLING OFFICE NAME AND ADDRESS: Department of the Army, Coastal Engineering Research Center, Kingman Building, Fort Belvoir, Virginia 22060	12. REPORT DATE: July 1979
	13. NUMBER OF PAGES: 31
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*	15. SECURITY CLASS. *(of this report)*: UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

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17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Breakwaters	Concrete armor units	Scale effects
Coastal engineering	Quarrystone	Wave runup
Coastal structures	Runup	Waves

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The results of previous tests of monochromatic wave runup on both smooth and rough slopes were reanalyzed. A method is presented for estimating wave runup on coastal structures with rough surfaces. This method is an extension of procedures described in the Shore Protection Manual (SPM)(U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). Where data were not presently available, the method uses the wave runup on smooth slopes and then adjusts the value by a rough-slope runup correction factor to determine

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the wave runup on rough slopes.

Flow charts are included to assist in choosing the proper procedures for determining wave runup on rough-slope structures with different types of permeability (i.e., embankment, rubble mounds with quarrystone or concrete armor units).

Example problems are presented illustrating the methods and procedures.

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PREFACE

This report describes a means of estimating wave runup on coastal structures with rough surfaces, and is a companion report to CETA 78-2, "Revised Wave Runup Curves for Smooth Slopes" (Stoa, 1978b). The report is based principally on analyses of laboratory experiments as discussed in TP 78-2 (Stoa, 1978a). The work was conducted under the structure-sediment-hydraulic interaction part of the coastal engineering research program of the U.S. Army Coastal Engineering Research Center (CERC).

The technical guidelines presented in this report expand on the methodology for determining wave runup on rough slopes presented in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). This report presents design curves for particular slope and wave conditions, and a procedure to estimate rough-slope runup as a function of runup on a comparable smooth slope for untested conditions. Smooth-slope runup curves are given in TP 78-2 and CETA 78-2 (Stoa, 1978a, 1978b) and should be reviewed for a more complete understanding of wave runup. Monochromatic waves are used here exclusively. Ahrens (1977) has presented a method for estimating irregular runup after monochromatic wave runup (considered to be from the significant wave) has been determined. Sketches of structures in this report are meant to illustrate principles of runup and laboratory tests; they do not necessarily indicate proper design for field application.

This report was prepared by Philip N. Stoa, Oceanographer, under the general supervision of Robert A. Jachowski, Chief, Coastal Design Criteria Branch.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

d water depth

d_s water depth at toe of structure

g acceleration of gravity (32.2 feet per second squared or 9.81 meters per second squared)

H wave height

H'_o the deepwater wave height equivalent to the observed shallow-water wave height assuming no refraction and friction

K_s shoaling coefficient, H/H'_o

k_r a length dimension of armor units

L wavelength in a water depth, d

L_o deepwater wavelength; wavelength in water depth, d, such that $d/L \geq 0.5$

R runup; the vertical rise of water on a structure face resulting from wave action

r ration of rough-slope runup to smooth-slope runup; rough-slope runup correction factor

T wave period

β bottom slope; used for the slope fronting a structure and is different from the structure slope

θ structure slope; may be beach slope if runup on the beach face is being investigated

WAVE RUNUP ON ROUGH SLOPES

by
Philip N. Stoa

I. INTRODUCTION

Prediction of wave runup on coastal structures is necessary to determine an adequate crest elevation if overtopping is to be prevented, or to help determine the extent of overtopping. Most protective structures in high-energy areas have rough, highly permeable, surfaces which absorb wave energy and reduce runup, but experimental studies of runup on rough slopes are complex. Consequently, runup studies have usually been limited in scope or have dealt with smooth slopes. Very few runup studies have been conducted on rough slopes using waves which break at or near the structure toe, yet this is often the design condition. This report presents a method of estimating wave runup for these conditions, as well as more detailed predictions for other wave conditions specifically tested in the laboratory. (See Stoa, 1978a, for background information.)

II. DEFINITION OF TERMS

Variables used in this and related reports (Stoa 1978a, 1978b) are shown in Figure 1 and are defined as: R, runup; θ, angle of structure face with horizontal; d, water depth; d_s, water depth at toe of structure; β, angle of bottom slope at structure toe; and h_c, height of core above toe of structure. Not shown in Figure 1 is K_r, the armor-unit length dimension. For quarrystone, K_r is the nominal diameter; for concrete armor units, K_r is a specified length dimension. L and H are the wavelength and wave height, respectively, in water depth, d. The same wave may be described by an equivalent deepwater wave ($d/L \geq 0.5$) for which the dimensions would be L_o and H_o'. L_o is the deepwater wavelength and may be determined if the wave period, T, is known ($L_o = gT^2/2\pi$). H_o' is the equivalent unrefracted deepwater wave height and is used because it avoids the problem of defining the wave height in varying depths over a sloping bottom where the wave may already have broken. The wave height in deep water is related to the unbroken wave height in a shallower depth by the shoaling coefficient, $K_s = H/H_o'$. The shoaling coefficient and wavelength, L, may be determined from Tables C-1 or C-2 in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) when L_o and the depth, d, are known.

III. METHODS OF DATA PRESENTATION

Results of runup experiments are presented in two forms. The first form is more detailed and is used for results of tests which covered a wide range of conditions. Relative runup, R/H_o', is given by a set of design curves and is a function of structure slope ($\cot \theta$), wave steepness parameter (H_o'/gT^2), relative depth (d_s/H_o'), and relative stone size (H_o'/k_r).

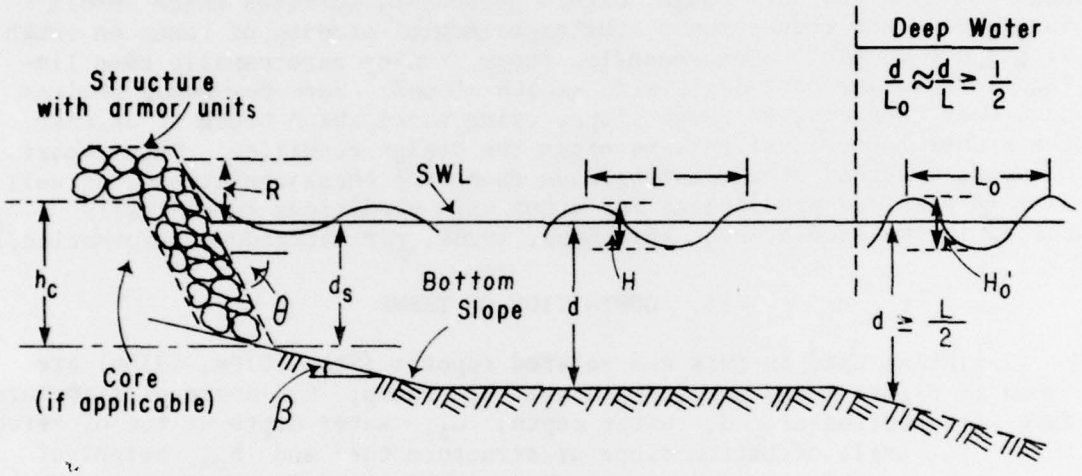

Figure 1. Definition sketch of variables applicable to wave runup.

The second form is simplified and is used for results of tests which had more limited slope and wave conditions. This form can also be used to estimate runup for wave conditions for which runup data are not available. Runup on a rough slope is expressed as a function of the runup on a smooth slope, where

$$r = \frac{R_{rough\ slope}}{R_{smooth\ slope}} = \frac{\left(R/H'_o\right)_{rough\ slope}}{\left(R/H'_o\right)_{smooth\ slope}} \text{ or } \frac{\left(R/H'_o\right)_{rs}}{\left(R/H'_o\right)_{ss}} .$$

The values of r given in this report were determined by comparisons of rough-slope runup with the smooth-slope runup curves given in Stoa (1978a). These smooth-slope runup curves differ in some respects from those given in the SPM; the revised curves are also given in Stoa (1978b) which should be used to determine the appropriate smooth-slope runup for use with the value of r. Smooth-slope runup values should not be corrected for scale effect as required in Stoa (1978b) if the runup values are being used with r values.

The tabulated values of r used here were selected for armor-unit relative sizes, H'_o/k_r, corresponding to design conditions (i.e., the necessary armor weight for an incident wave) as determined from design procedures given in the SPM. Larger armor units (smaller values of H'_o/k_r) should produce a more stable structure. This would also have the effect of reducing runup because of the increased roughness; smaller armor units may be unstable for the design wave conditions.

IV. DETERMINATION OF RUNUP

Rough-slope runup is determined by means of flow charts (Figs. 2, 3, and 4). Figure 2 shows the selection process for determining runup on embankments (i.e., revetment or a similar type of impermeable structure); Figures 3 and 4 show the selection process for determining runup on rubble-mound structures. Results are given in Appendixes A to F.

Each value of r, as originally given in Stoa (1978a), was an average for several wave steepness parameters (H'_o/gT^2) at specific d_s/H'_o and H'_o/k_r values. Thus, they did not reflect the data extremes and should be considered approximate. Values of r given in this report were selected for the higher values of H'_o/k_r, approaching the limits of armor-unit stability, or for values of H'_o/k_r as noted.

The r values must be considered only as approximate solutions; the design curves in Appendixes B and E should be used if possible. However, *comparisons* of runup for different wave conditions should use the same method of runup determination; i.e., either the curves or r values.

Scale-effect corrections, as given in the flow charts (Figs. 2, 3, and 4), are from Stoa (1978a). If runups from a range of wave conditions are being compared, it is preferable to make the comparison before application of scale-effect corrections.

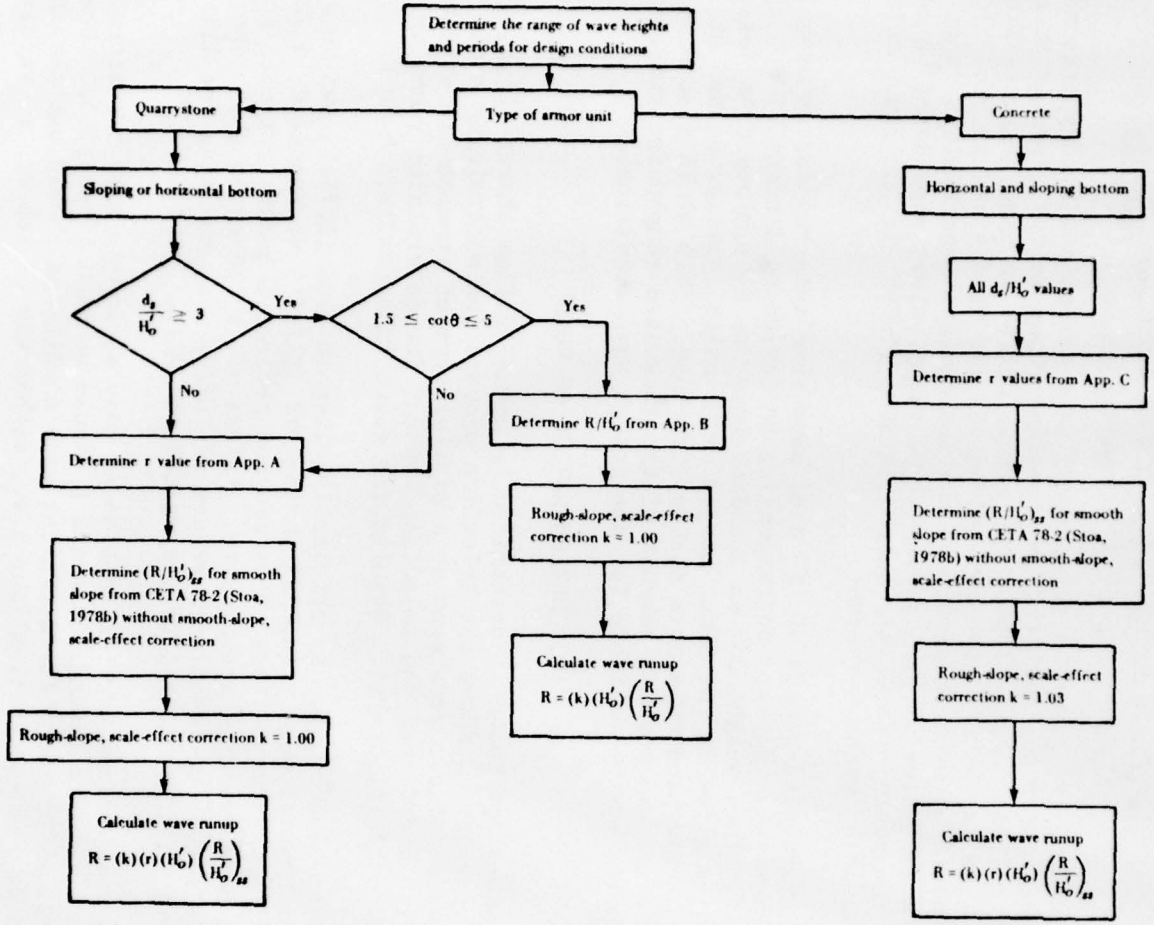

Figure 2. Flow chart for determination of runup on an embankment (quarrystone riprap or concrete armor units).

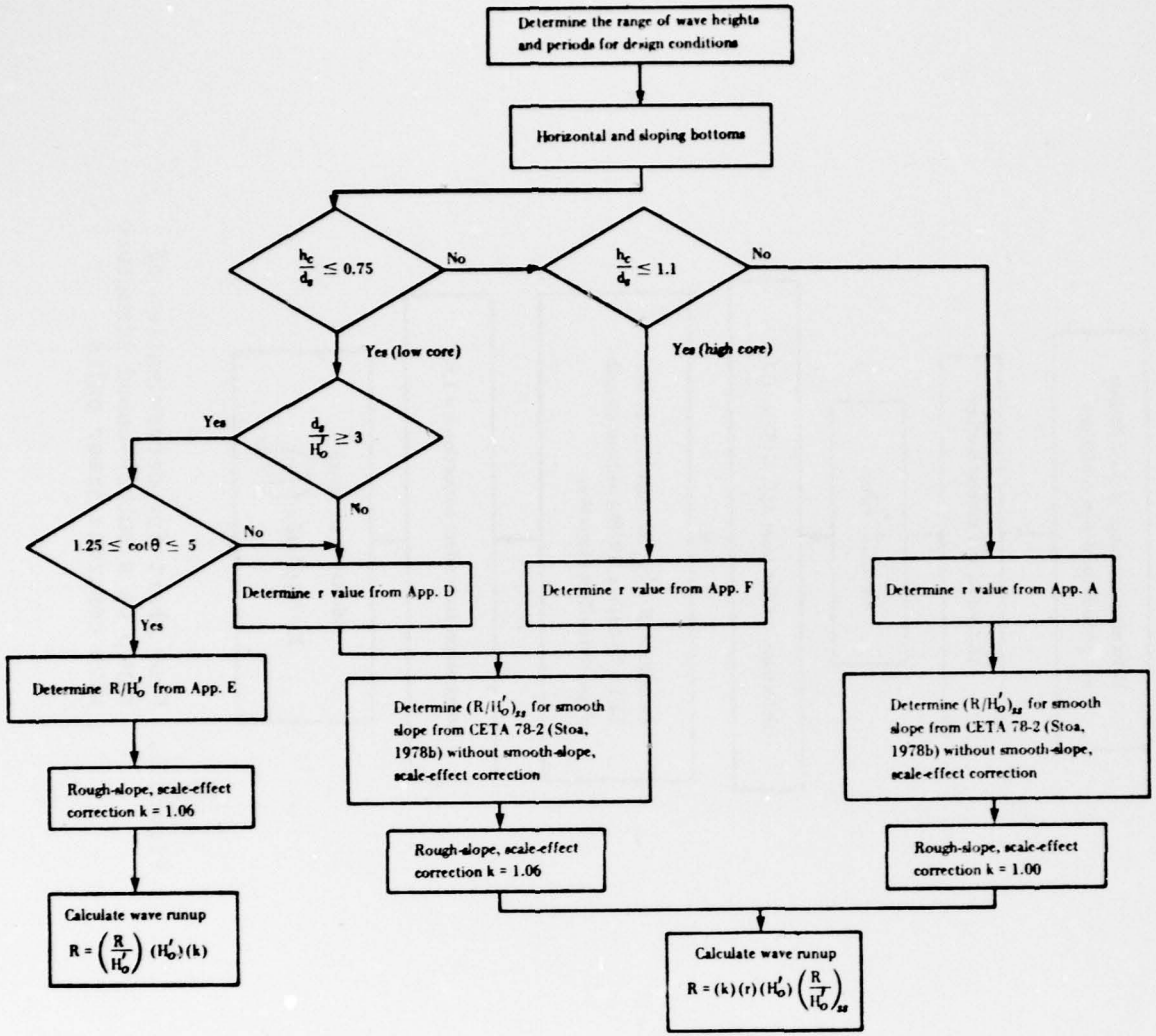

Figure 3. Flow chart for determination of runup on a quarrystone rubble-mound structure.

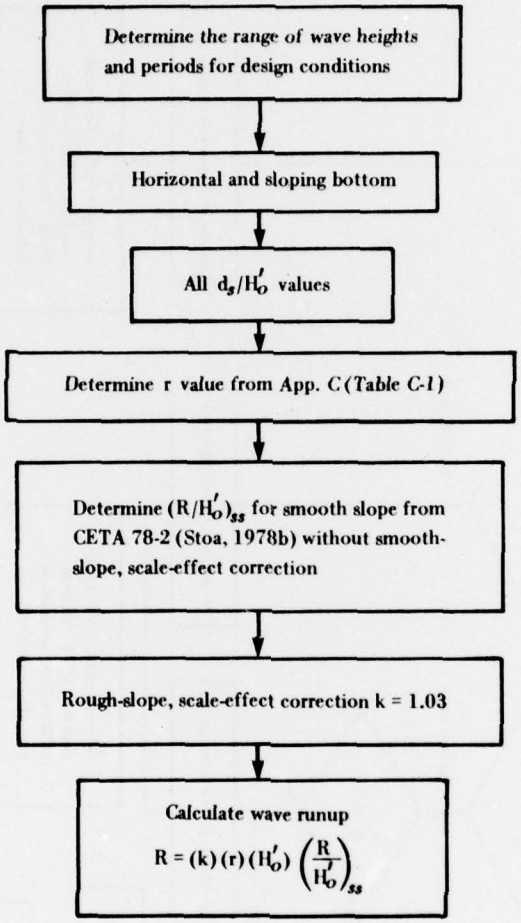

Figure 4. Flow chart for determination of runup on a rubble-mound structure with concrete armor units.

Use of the flow chart, design curves, and r values are demonstrated in the following example design problems.

V. EXAMPLE DESIGN PROBLEMS

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 1 * * * * * * * * * * * * * * *

GIVEN: Embankment with quarrystone riprap; cot $\theta = 2$; cot $\beta = 0$; $d_s = 10$ feet (3 meters); $H'_o = 2$ feet (0.61 meter); $T = 3$ seconds; $k_r \simeq 0.7$ foot (0.21 meter).

FIND: Wave runup (use one of the flow charts in Figs. 2, 3, or 4).

SOLUTION: Since the structure is defined as an embankment, use the flow chart in Figure 2 as follows:

(a) Type of armor unit is quarrystone.

(b) Bottom slope is cot $\beta = 0$ (i.e., horizontal).

(c) $\frac{d_s}{H'_o} = \frac{10}{2} = 5$ (i.e., > 3).

(d) Structure slope is cot $\theta = 2$ (i.e., between 1.5 and 5).

(e) Therefore, determine R/H'_o from Appendix B.

(f) For $\frac{d_s}{H'_o} = 5$, use Figure B-2, and

(g) $\frac{H'_o}{K_r} = \frac{2}{0.7} = 2.8 \simeq 3.0$, with

(h) $\frac{H'_o}{gT^2} = \frac{2}{(32.2)(3)^2} = 0.0069.$

(i) Therefore, $\frac{R}{H'_o} \simeq 1.18$.

(j) From Figure 2, scale effect is $k = 1.00$.

(k) Finally, from Figure 2,

$$R = \left(\frac{R}{H'_o}\right)(H'_o)\ (k)$$

$$= (1.18)(2)(1.0)$$

$$R = 2.36 \text{ feet} \simeq 2.4 \text{ feet (0.73 meter).}$$

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 2 * * * * * * * * * * * * * * *

GIVEN: Rubble-mound breakwater with quarrystone for armor; cot θ = 2.5; cot β = 80; d_s = 18 feet (5.5 meters); H'_o = 6 feet (1.8 meters); T = 5 seconds; k_r = 2 feet (0.61 meter); h_c = 13 feet (4 meters).

FIND: Wave runup (use one of the flow charts in Figs. 2, 3, or 4).

SOLUTION: Since the structure is a quarrystone rubble mound, use the flow chart in Figure 3 as follows:

(a) $\frac{h_c}{d_s} = \frac{13}{18} = 0.72$ (i.e., $\frac{h_c}{d_s} < 0.75$; therefore, this structure has a low core).

(b) $\frac{d_s}{H'_o} = \frac{18}{6} = 3$ (i.e., "yes," $\frac{d_s}{H'_o} \geq 3$).

(c) Structure slope is cot θ = 2.5 (i.e., "yes," cot θ is between 1.5 and 5).

(d) Therefore, determine R/H'_o from Appendix E.

(e) For $\frac{d_s}{H'_o} = 3$, use Figure E-1.

(f) $\frac{H'_o}{k_r} = \frac{6}{2} = 3$. (This value is smaller than that used in Fig. E-1; the smaller value indicates a larger stone size for a given wave height, which would further reduce the runup from that given in Fig. E-1; thus, runup predicted from Fig. E-1 may be considered conservative, i.e., as larger or larger than the actual runup to be expected.)

(g) $\frac{H'_o}{gT^2} = \frac{6}{(32.2)(5)^2} = 0.00745.$

(h) From Figure E-1, with cot θ = 2.5, $\frac{R}{H'_o} = 0.80$.

(i) From Figure 3, scale effect is k = 1.06.

(j) Finally, from Figure 3,

$$R = \left(\frac{R}{H'_o}\right)(H'_o)\ (k)$$

$$R = (0.8)(6)(1.06)$$

$$R = 5.1 \text{ feet (1.6 meters)}.$$

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 3 * * * * * * * * * * * * * * *

GIVEN: A rubble-mound breakwater with concrete tetrapod armor units on the structure trunk; d_s = 20 feet (6.1 meters); cot θ = 2; cot β = 20. The structure is being designed for the maximum wave height at the toe depth; the longest wave period expected is 11 seconds. From design methods (see SPM, Ch. 7), the following are determined: breaker height, H_b, is 23.4 feet (7.1 meters) and H'_o = 18.7 feet (5.7 meters).

FIND: Wave runup on the breakwater trunk; assume the waves are approaching normal to the structure.

SOLUTION: The structure is a breakwater with concrete armor units; therefore, the flow chart in Figure 4 is used, as follows:

(a) From Appendix C, and assuming the tetrapods will be placed randomly and in a two-unit armor-layer thickness,

$$r \simeq 0.45 \ .$$

(b) From Stoa (1978b), a value of R/H'_o for a smooth slope is determined by first finding d_s/H'_o and H'_o/gT^2,

$$\frac{d_s}{H'_o} = \frac{20}{18.7} = 1.07$$

$$\frac{H'_o}{gT^2} = \frac{18.7}{(32.2)(11)^2} = 0.0048 \ .$$

From Figure 9 in CETA 78-2 (Stoa, 1978b), and without correcting for smooth-slope scale effects,

$$\left(\frac{R}{H'_o}\right)_{smooth\ slope} = 2.7 \ .$$

(c) Again, following Figure 4 of this report, the scale-effect correction is

$$k \simeq 1.03 \ .$$

(d) Runup on this rough slope is

$$R = \left(\frac{R}{H'_o}\right)_{smooth\ slope} (H'_o)(r)(k)$$

$$= (2.7)(18.7)(0.45)(1.03)$$

$$R = 23.4 \text{ feet } (7.13 \text{ meters})$$

* *

VI. SUMMARY

This report presents methods for estimating runup on rough slopes. Estimates are based either on design curves or on correction factors which are applied to runup values determined for smooth slopes; smooth-slope runup is determined by use of design curves in CETA 78-2 (Stoa, 1978b). The rough-slope runup estimates are then corrected for scale effects as applicable.

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APPENDIX A

VALUES OF r FOR QUARRYSTONE EMBANKMENT; $d_s/H'_o < 3$

Table A-1. Values of r for application at $d_s/H'_o < 3$.

Slope (cot θ)	H/k_r [1]	r
1.5	3 to 4	0.60
2.5	3 to 4	0.63
3.5	3 to 4	0.60
5.0	3	0.60
5.0	4	0.68
5.0	5	0.72

[1] H'_o was used to derive these values from experiments with $d_s/H'_o > 3$; for application at $d_s/H'_o < 3$, use H, where H is the wave height at the proposed structure location.

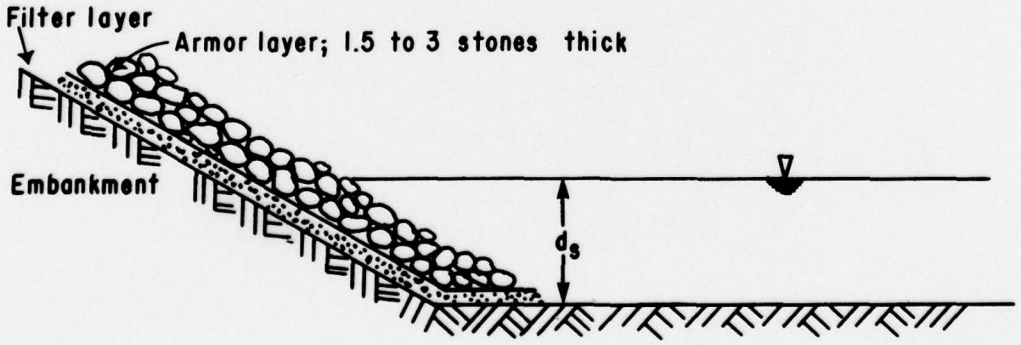

Figure A-1. Sketch of quarrystone embankment (riprap).

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APPENDIX B

DESIGN RUNUP CURVES FOR QUARRYSTONE EMBANKMENT; $d_s/H_o' \geq 3$

Relative runup for riprap slopes is shown in Figures B-1, B-2, and B-3 for $d_s/H_o' = 3$, $d_s/H_o' = 5$, and $d_s/H_o' = 8$, respectively. Figure B-3 was derived specifically for $d_s/H_o' = 8$, but is also used for $d_s/H_o' > 8$.

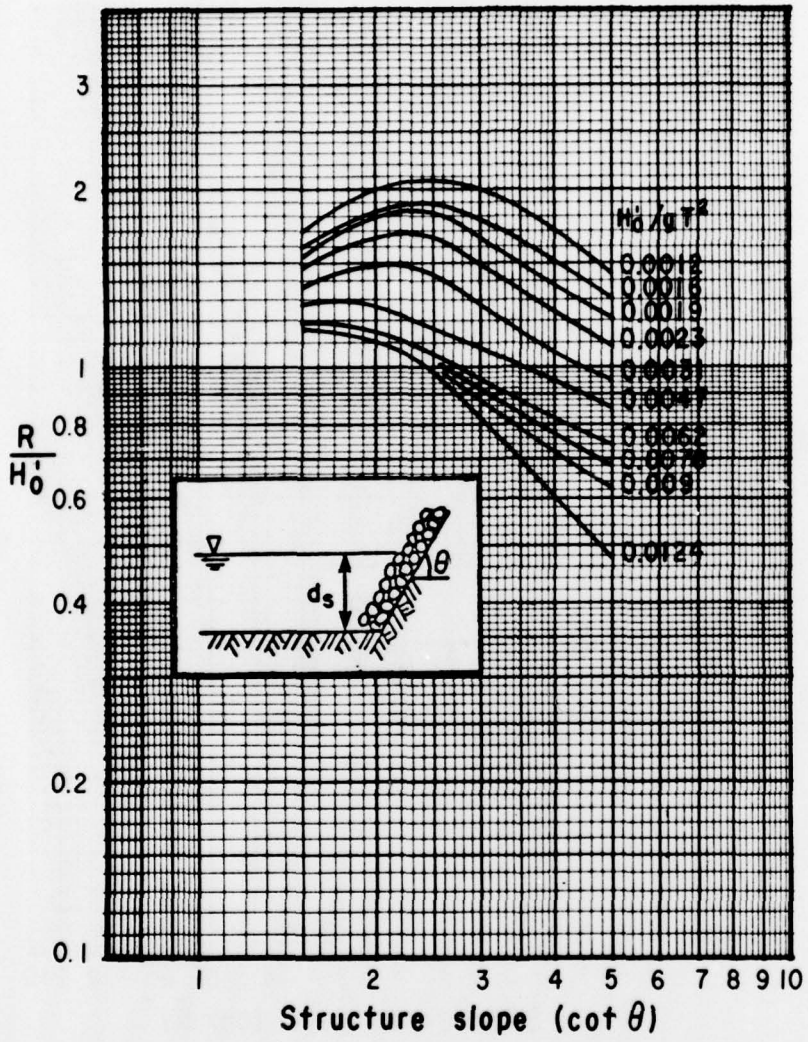


Figure B-1. Relative runup for riprap slopes; d_s/H'_O = 3.0; $H'_O/k_r \simeq 3.0$ (after Stoa, 1978a).

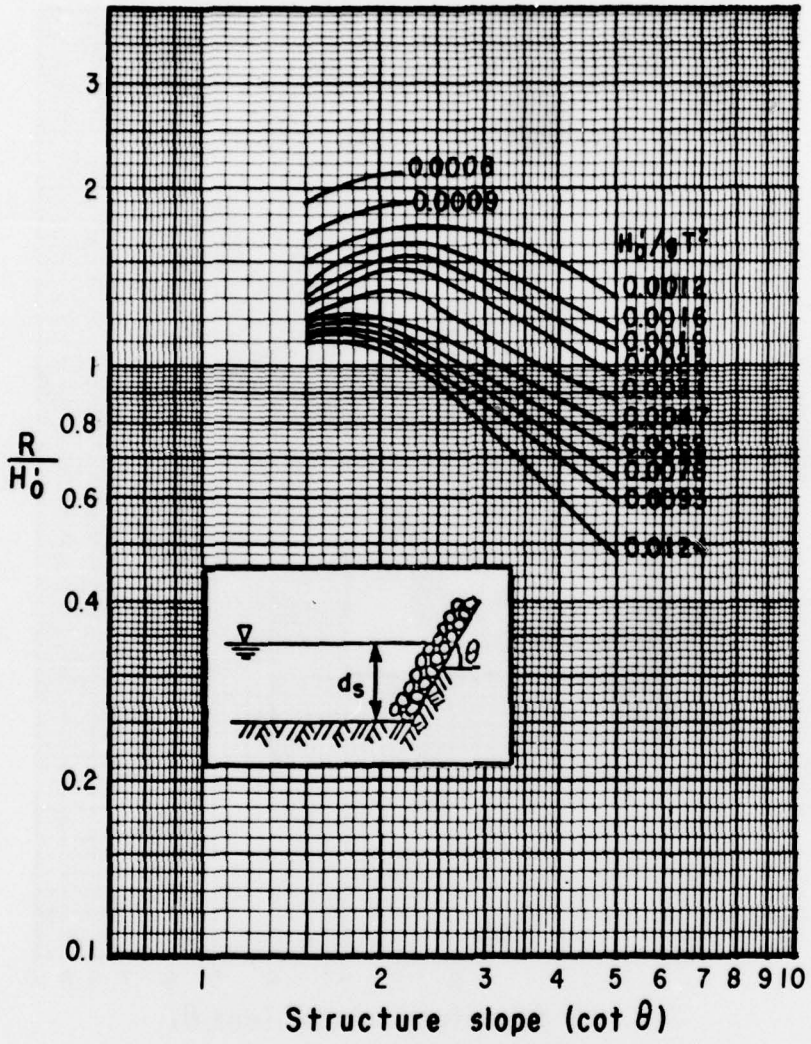


Figure B-2. Relative runup for riprap slopes; $d_s/H'_O = 5.0$; $H'_O/k_r \simeq 3.15$ (after Stoa, 1978a).

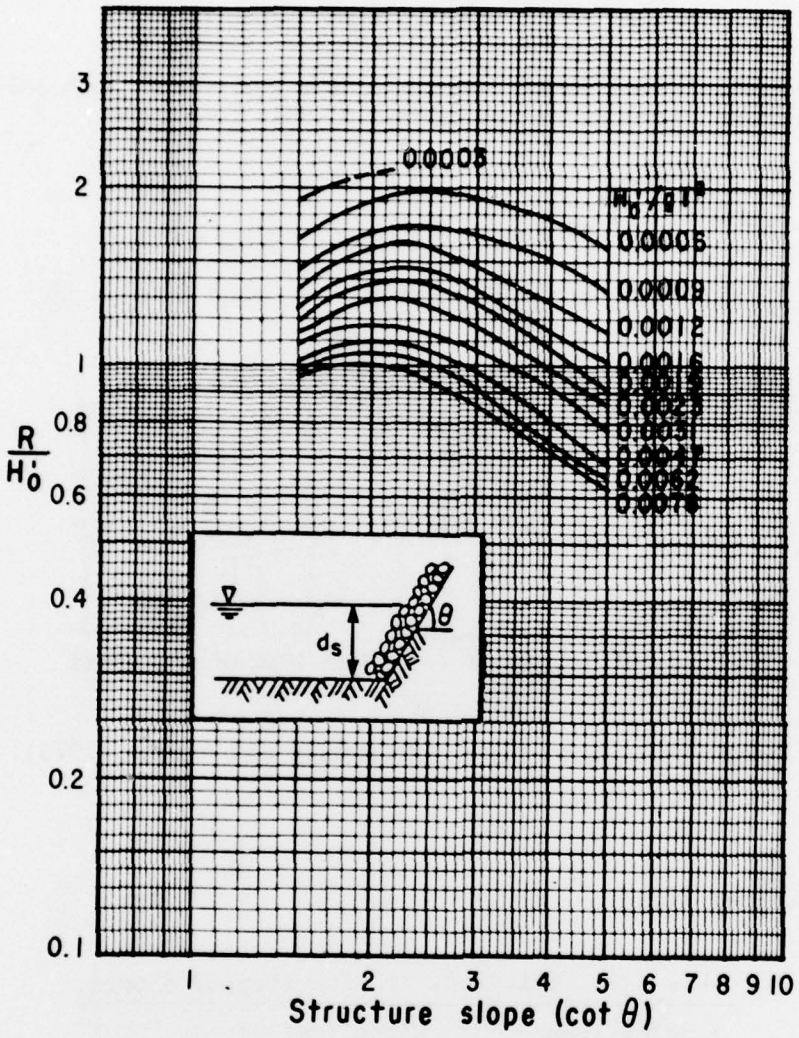


Figure B-3. Relative runup for riprap slopes; d_s/H'_o = 8.0; H'_o/k_r ≈ 2.8 (after Stoa, 1978a).. Use this figure also for d_s/H'_o > 8.0.

APPENDIX C

VALUES OF r FOR CONCRETE ARMOR UNITS

1. Embankment. (Additional concrete units for use on both embankments and rubble-mound structures are given in Table C-2.)

a. Gobi Blocks.

$$r \approx 0.93 \text{ for } H'_o/k_r \text{ or } H/k_r \approx 6$$

(use H'_o when $d_s/H'_o \geq 3$ and H when $d_s/H'_o < 3$)

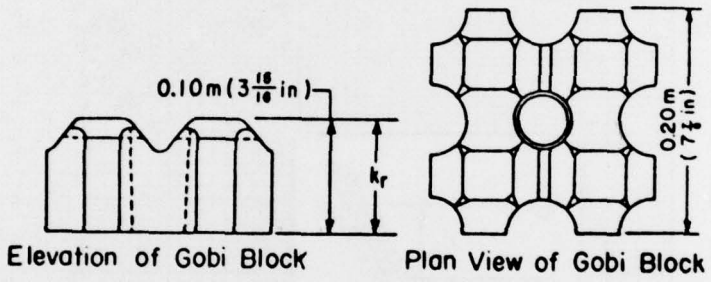


Figure C-1. Gobi block (McCartney and Ahrens, 1975).

b. Stepped Slopes.

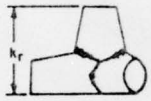
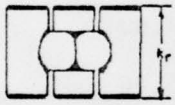
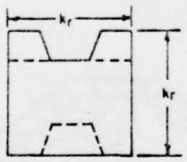
Table C-1. Values of r for stepped slopes.

Type of step	Slope (cot θ)	r [1]
Vertical risers	1.5	0.75
	2.0	0.75
	3.0	0.70
Rounded edges	3.0	0.86

[1] $1 < H'_o/k_r \leq 12$ where k_r is the height of the riser.

2. Embankment and Rubble Mound.

Table C-2. Values of r for concrete armor units.

Armor unit and placement method	Length dimension, k_r	Armor-layer thickness (No. of units)	Values of r	Slopes (cot θ)
Tetrapod				
Random		2	0.45	1.3 to 3.0
Uniform		2	0.51	1.3 to 3.0
Quadripod				
Random		2	0.51	1.3 to 3.0
Uniform		2	0.51	1.3 to 3.0
Tribar				
Random		2	0.45	1.3 to 3.0
Uniform		1	0.50	1.3 to 3.0
Modified cube				
Random		2	0.48	1.3 to 3.0
Uniform		1	0.62	1.5
Uniform		1	0.73	2.0
Uniform		1	0.55	3.0

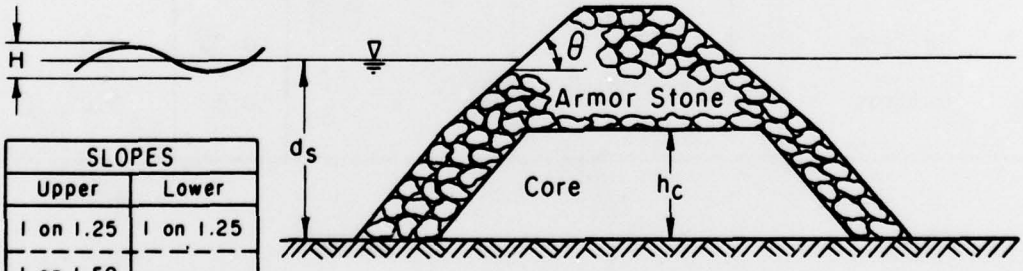
APPENDIX D

VALUES OF r FOR QUARRYSTONE RUBBLE-MOUND STRUCTURE

(LOW CORE; $d_s/H'_o < 3$)

Table D-1. Values of r for quarrystone rubble mound.

Wave and structure conditions	slope (cot θ)	r
$\frac{d_s}{H'_o} < 3$,	1.25	0.57
	1.50	0.45
$\frac{h_c}{d_s} \leq 0.75$	2.00	0.44
	2.50	0.42
	3.00	0.44
	4.00	0.48
	5.00	0.48



SLOPES	
Upper	Lower
1 on 1.25	1 on 1.25
1 on 1.50 1 on 2.00 1 on 2.50	1 on 1.50
1 on 3.00 1 on 4.00 1 on 5.00	1 on 2.00

Figure D-1. Sketch of low-core rubble-mound structure used for experiments.

APPENDIX E

DESIGN RUNUP CURVES FOR QUARRYSTONE RUBBLE-MOUND STRUCTURE

(LOW CORE; $d_s/H'_o \geq 3$)

Quarrystone rubble-mound runup is shown in Figures E-1, E-2, and E-3 for $d_s/H'_o = 3$, $d_s/H'_o = 5$, and $d_s/H'_o = 8$, respectively. Figure E-3 was derived specifically for $d_s/H'_o = 8$, but is also used for $d_s/H'_o > 8$.

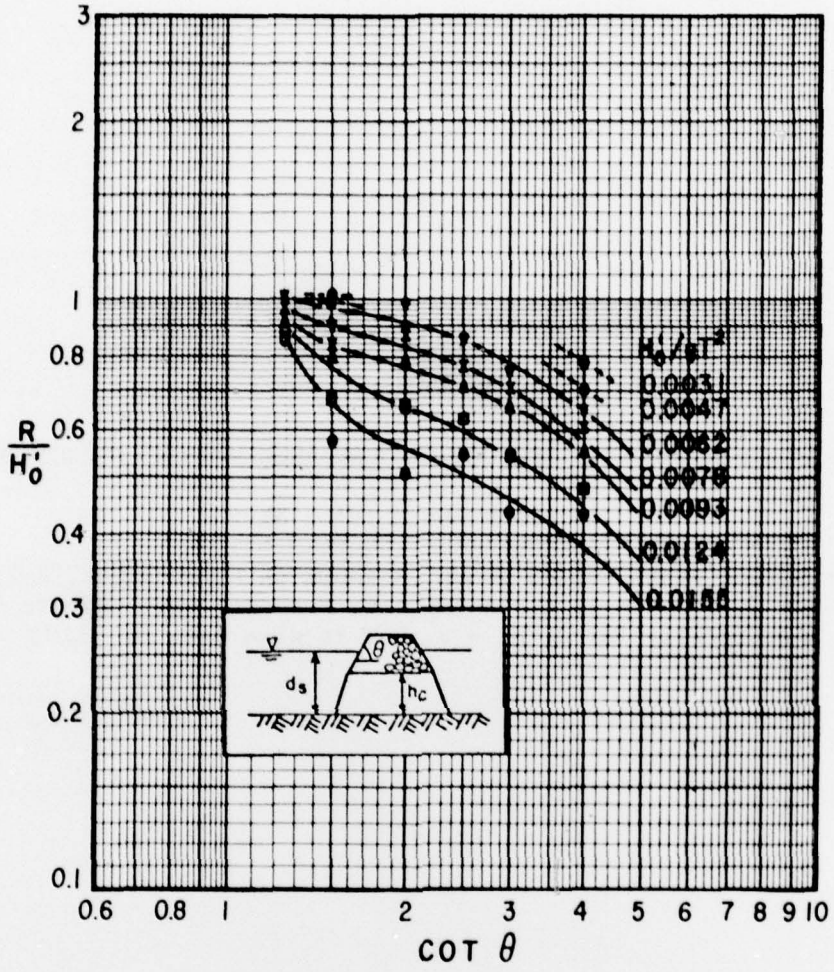


Figure E-1. Quarrystone rubble-mound runup; $d_s/H'_0 = 3.0$; $H'_0/k_p = 4.5$; $h_c/d_s \simeq 0.75$ (after Stoa, 1978a).

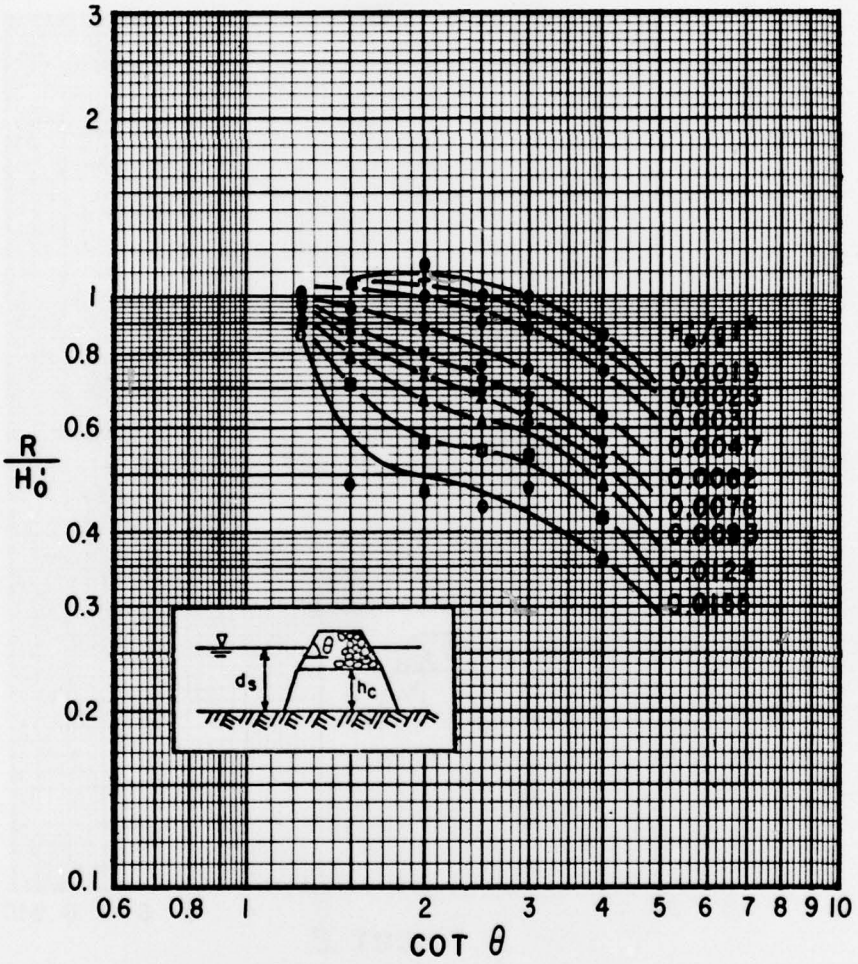


Figure E-2. Quarrystone rubble-mound runup; d_s/H'_o = 5.0; H'_o/k_r = 2.7; $h_c/d_s \simeq 0.75$ (after Stoa, 1978a).

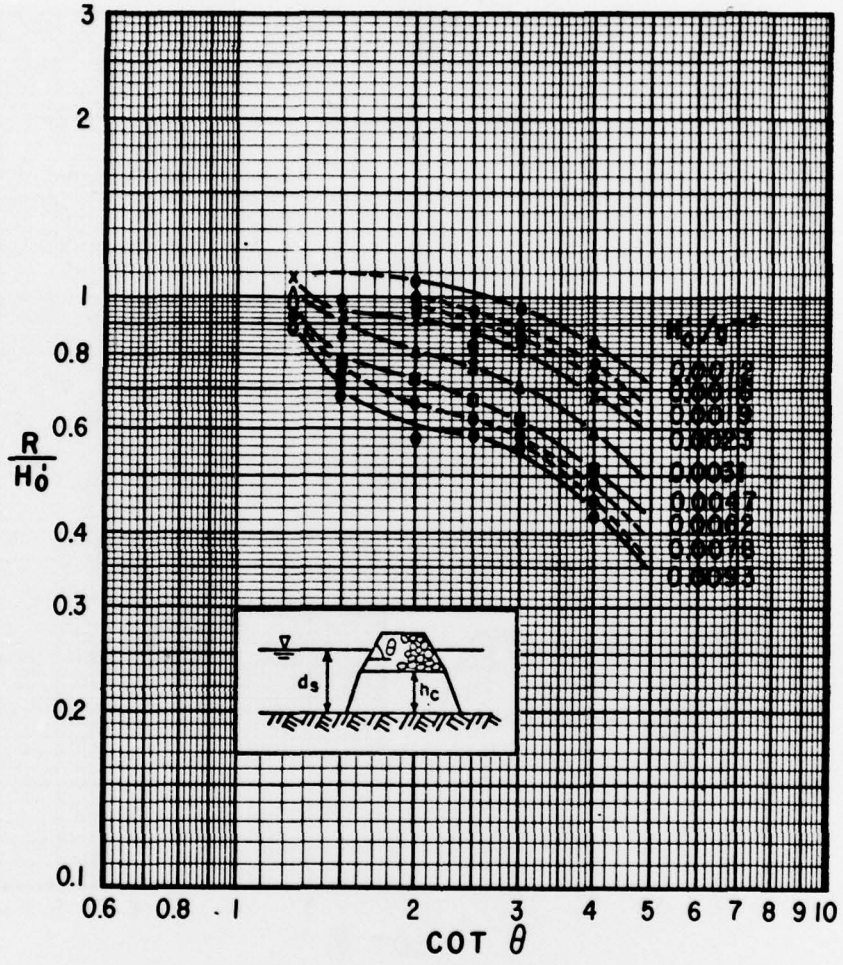


Figure E-3. Quarrystone rubble-mound runup; d_s/H'_o = 8.0; H'_o/k_r = 1.7; h_c/d_s ≃ 0.75 (after Stoa, 1978a)

APPENDIX F

VALUE OF r FOR QUARRYSTONE RUBBLE-MOUND STRUCTURE (HIGH CORE)

r = 0.52

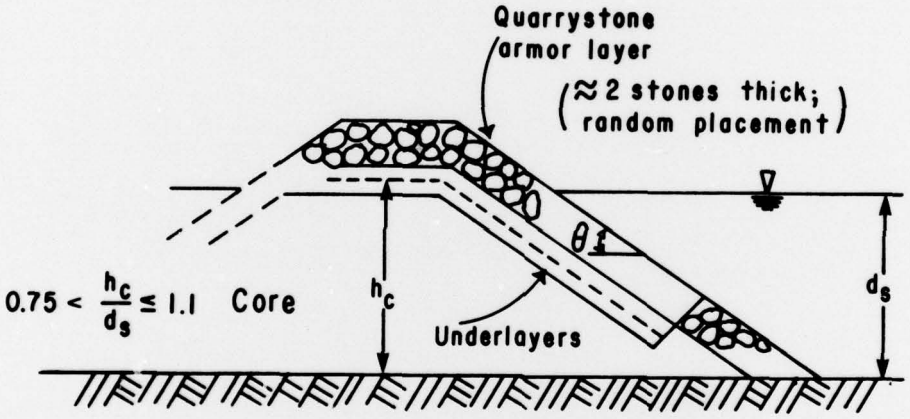


Figure F-1. Sketch of high-core rubble-mound structure.

Stoa, Philip N.

Wave runup on rough slopes / by Philip N. Stoa. - Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.
31 p. : ill. ; 27 cm. - (Coastal engineering technical aid - U.S. Coastal Engineering Research Center : CETA 79-1)
Bibliography : p. 17.
Previous test results of monochromatic wave runup on smooth and rough slopes are reanalyzed. Report presents a method for estimating wave runup on coastal structures with rough surfaces. Flow charts are included to assist in determining runup on structures with different permeabilities; example problems are also given.

1. Wave run-up. 2. Breakwaters. 3. Scale effects. I. Title. II. Series: U.S. Coastal Engineering Research Center. Coastal engineering technical aid. CETA 79-1.

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